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Contract No.: DAAK40-79-C-0212

AUTOMATED FACILITIES REPORT

Prepared for

U.S. ARMY MISSILE COMMAND
DRSMI-ET
Redstone Arsenal, Alabama
Project Office: Gorden D. Little

By

WESTINGHOUSE ELECTRIC CORPORATION
Defense and Electronic Systems Center
Baltimore, Maryland

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO. AD-A098 035	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Flexible Printed Circuits With Integral Molded Connectors Automated Facilities Report		5. TYPE OF REPORT & PERIOD COVERED
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Richard L. Hall		8. CONTRACT OR GRANT NUMBER(s) DAAK40-79-C-0212
9. PERFORMING ORGANIZATION NAME AND ADDRESS Westinghouse Defense & Electronic System Center		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS US Army Missile Command Redstone Arsenal, Alabama 35898 Gordon D. Little Project Officer		12. REPORT DATE 3/12/81
		13. NUMBER OF PAGES
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) Air Force Plant Representation Office (AFPRO)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Unlimited

DISTRIBUTION STATEMENT A

Approved for public release;
Distribution Unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Flexicon	Ablation	Automated Facility
Flexible Printed Wiring	Welding	Processes
Flexible Circuits	Liquid Injection Molding	
Connectors	LIM	
Laser	Automation	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Three new processes used in termination of Flexible Printed Wiring (FPW) to connectors were developed on this program. They are laser ablation (removal) of insulation by CO_2 Laser, laser welding by Nd:YAG Laser, and liquid injection molding of small parts. The integration of these processes into a fully automated facility capable of one assembly per minute production was then projected (Automated Facility Report).

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1.0 THE FLEXICON PROCESS

1.1 Introduction:

This paper describes an automated process for the production of integral molded connector terminations on flexible printed wiring (FPW). The design was undertaken as part of a Manufacturing Methods and Technology contract with the U.S. Army Missile Command, Redstone Arsenal, Alabama.

The process features the application of industrial laser techniques to the requirements of FPW stripping and to the welding of the copper foil circuit leads to the connector pins. Also, the utilization of fast-cure liquid resin injection molding (L.I.M.) permits inclusion of connector to flex circuit encapsulation as part of the in-line process.

The automated process is designed to handle planar two row connectors on .050" centers at a production rate of 500 connector assemblies per 8 hour shift. This paper deals with the specific design requirements for automated part handling and positioning to accomplish reliable, low cost FPW termination and encapsulation.

1.2 Benefits of the Automated Process

The automation of any fabrication process must be able to control that process within all tolerance extremes to ensure consistently good output. Also, this automation must minimize human intervention to increase the process reliability. If an operation must be performed under human control, it is affected by all of the possible variables of the human. If it can be reliably

controlled by a machine, then the machine variables affect the output. In simple machines, those variables may only be tool wear or loss of power. Thus the second most important reason for full automation is consistency of output. The first benefit is cost.

In considering the cost effectiveness of the automated facility outlined in this report, the basic costs have been broken into two groups, capital and recurring. Capital costs include basic equipment and maintenance. Recurring costs include material and labor for the product being produced. Detailed analysis shows that capital expenses will be about equal to those required for competitive processes at the same production rates. Recurring costs, cost of goods and services, are one-sixth those encountered with existing alternatives.

With the combination of consistency of product (reliability) and significantly lower cost, the philosophy of systems maintenance dramatically changes. Instead of repair of assembled units which might be damaged, replacement is the lowest life cycle cost alternative. Other secondary benefits add to the improved life cycle cost by increasing aircraft mission effectiveness because of an increased use of flexible printed wiring (FPW) and flat conducter cable (FCC) brought about by lower basic cost. These reduce required volume for interconnection and reduced interconnection weight by as much as 70 percent.

The development of processes which are tolerant of a wide span of parameters coupled with low recurring costs as primary benefits, coupled with effective secondary gains, provides a significant potential for return on investment of the fully automated facility.

To provide for an optimum usefulness of this approach to many systems and connectors, the maximum control of the processes through programmable software has been made. This minimizes hard tooling requirements to a few pieces, and establishes full control of all of the processes within the flexibility of the processor.

Processes and automation have been developed to meet a capability of fabrication of up to 500 assemblies per eight hour shift.

1.3 The Process Flow

The automated Flexicon process has three basic steps, laser stripping of the flexible printed wiring (FPW), laser welding termination of FPW leads to connector, and assembly encapsulation. The straight-line flow is charted in Figure 1. Under controlled conditions, a pulsed CO_2 laser is used to ablate the insulating material surrounding the copper leads in the area which is subsequently to be terminated to the connector. The focused light energy of 10.6 micron wavelength discriminates between the copper, which is highly reflective to this wavelength, and the plastic covering layers and the adhesive layers which readily absorb the energy. At the energy density levels used, this causes virtually instantaneous heating of the organic materials to vaporization temperature while leaving the copper undisturbed. A simple cleaning process involving bristle brush stroking and solvent wash of the exposed copper dislodges any particulate char which may remain.

A Neodymium: YAG pulsed laser is used to weld the copper leads to the contact tails of the connector. The focused light energy of 1.06 micron wavelength is readily absorbed, in this case, by the copper leads.

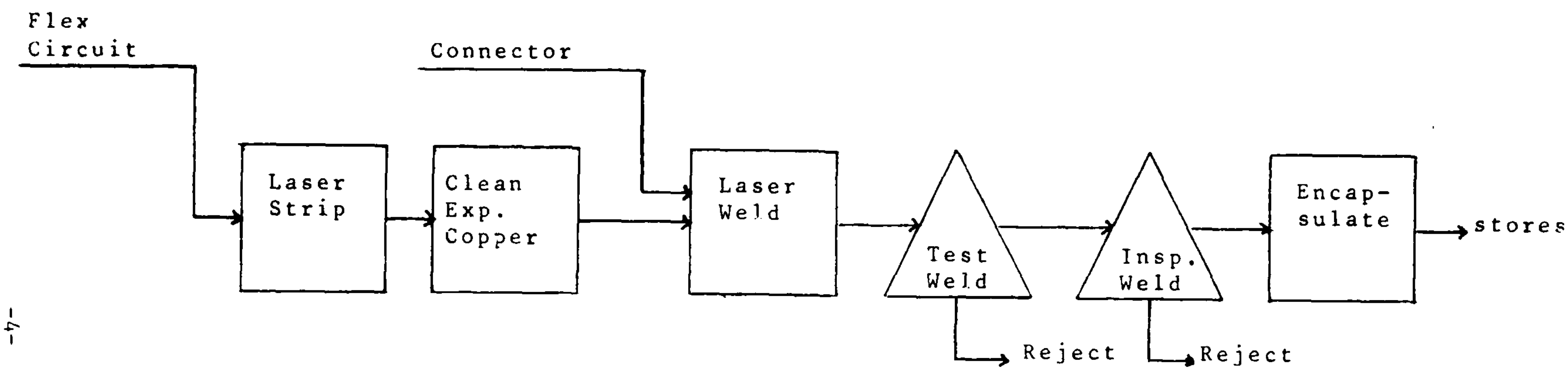


Figure 1 Automated Flexicon Process Flow

Absorption of the focused light energy rapidly raises the temperature of the metals to cause a fusion weld to be formed.

Automatic electrical test is performed on each weld termination to verify acceptable conductivity. Automatic visual inspection is an optional feature which may be implemented by several methods, for instance, use of the specular signature of an acceptable weld nugget as criterion in an electro-optical system.

Encapsulation which provides the necessary electrical isolation between adjacent leads and strain relief transition from connector to unsupported flex circuitry is the last process step. A quick-cure liquid resin system is utilized which makes it possible to automatically load the mold and encapsulate the Flexicon assemblies in line with the preceeding process steps. This avoids any manual handling of the relatively fragile assemblies before molding.

2.0 THE AUTOMATED SYSTEM DESIGN

2.1 System Design Strategy

The primary feature of the Flexicon Automated System is the application of programmable control to all aspects of the system in order to minimize the need for hardware type tooling dedicated to a specific Flexicon assembly. By utilizing programmable control, many aspects of machine and process parameters are removed from hardware definition and are brought under software definition. The benefit of software control is that while absolute fidelity to the program is maintained during the machine cycle, an infinite number of programs can be generated and rapidly changed to deal with assembly style changes or process variables. Accordingly, the geometric character of the connector and flexible circuit (ie., pitch and number of connector leads to be welded) are controlled by software and are easily changed or modified by software; with minor hardware modifications required.

In addition, the complexity of the automation type tooling required for this system has been greatly simplified by the microprocessor control. The precision motions required for guiding the flex circuit and assembly through stripping, welding, test/inspection, and mold loading are derived from the capability of the microprocessor to control the position of the x-y table and not from mechanical mechanisms intrinsic to the hardware itself.

The application of programmable control to the Flexicon system falls into three categories:

1. Control of Processes

- Laser Welding
- Laser Stripping
- Encapsulation

2. Control of Position

- Index Entrained Connectors
- Translate Flex Circuit past CO_2 Laser Beam
- Translate Assembly past Nd:YAG Laser Beam
- Load Welded Assembly into Encapsulation Mold

3. Control of System Timing

- Coordinate System Events in Series and Parallel

2.1.1 Control of Processes

Control of critical processes is the most desirable application of programmable control since precise, repeatable control of critical operations is achieved. In this sytem, for instance, software is utilized to precisely coordinate the laser spot welding with the position of the target. This is done by electronically counting position command pulses to the positioning table, which is translating the flexible printed wiring/connector assembly in the laser focal plane, and timing the laser firing command to the position count which corresponds to a flex lead connector in proper weld position. With this type control the welding of connector to the leads can be done quite rapidly, in fact, limited only by the time required to recharge the laser firing circuit between pulses.

In addition, a characteristic of a pulsed welding laser is the necessity to start the firing pulses in advance of the first weld in order to thermally

stabilize the lasing system and establish uniform energy density at the target. One way to achieve this is to start the train of laser pulses in advance of the first target and dissipate the energy into the system's closed shutter. The shutter is then timed to open just before the first weld target is in positon. Similarly, the laser stripping process is controlled by software; cover gas, vacuum, laser pulsing, and laser shutter control are also rigidly controlled by the software program. The injection molding process parameters (e.q. time and temperature) are precisely controlled by the program. They can be changed to new parameters by a change in the program.

Programmed control of position is accomplished by mounting some parts of the system hardware on two compounded, servo controlled, machine type linear slides. In-process Flexicon assemblies can thereby be moved in a horizontal plane relative to the fixed positions of the two lasers and the molding press.

2.1.2 Control of Position

In the second category, programmed control of position is accomplished by mounting the parts of the system hardware which support the assemblies on two compounded, servo controlled, machine type linear slides. In-process assemblies can thereby be moved in a horizontal plane relative to the fixed positions of the two lasers, the molding press and the FPW and connector inputs. The FPW is translated in the focal plane of the CO_2 stripping laser and also the Neodymium - YAG welding laser by software control of the positioning tables with no other mechanical assist required.

At any time in the operation of the system, there are up to seven assemblies in process. By means described in the next section, the assembly

can be indexed readily from one process station to the next by a programmed table motion controlled by the software. The flexible circuit is input to the process and translated in the focal plane of the CO_2 stripping laser and also the spot welding Neodymium YAG laser by software control of the positioning tables.

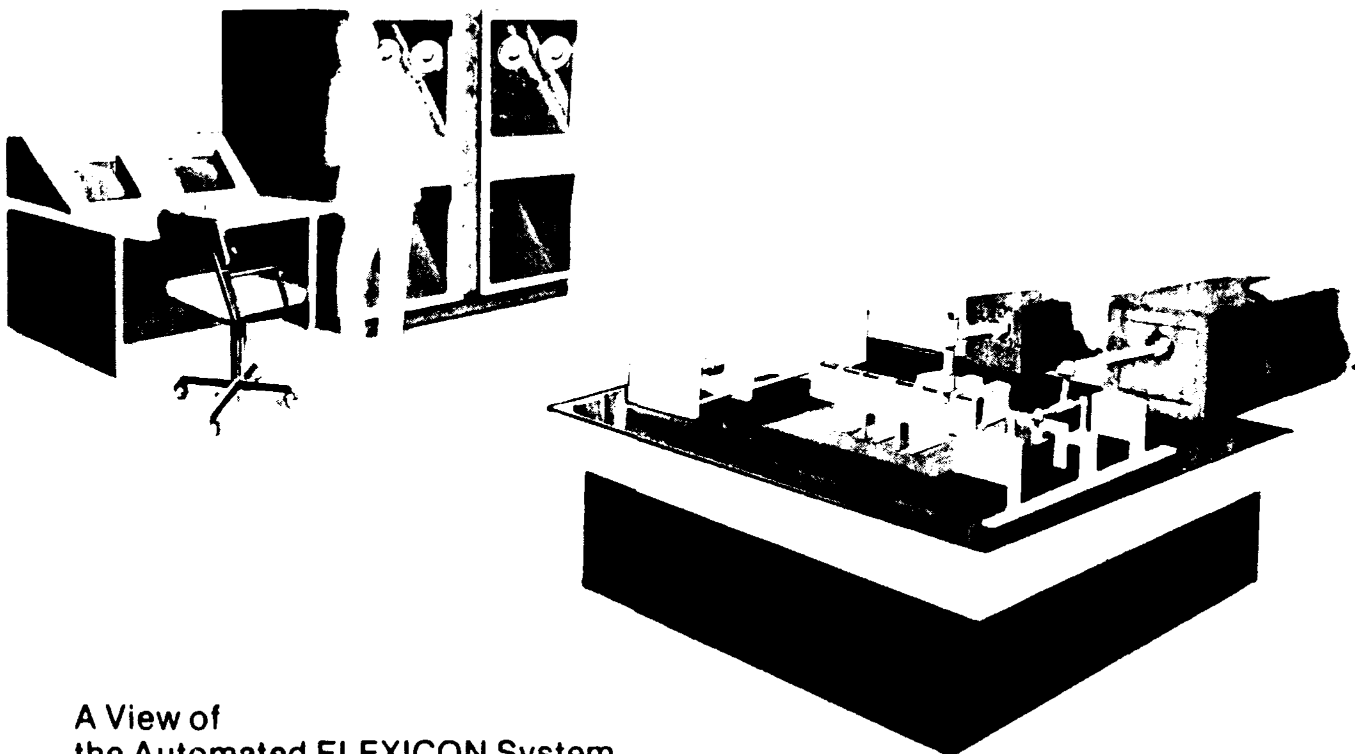
2.1.3 Control of System Timing

System timing is the third category where programmable control is applied. Event timing is an essential element in this automated system. In the section on kinematics in this report, it is shown how the many process events and motion routines are orchestrated by the software program. Extensive use has been made of programmed cues ported to external control hardware to initiate program sub-routines such as manipulation of the flex from input through laser stripping and subsequent transfer to the laser welding operation. A secondary feature of the automated system design is the integration of all three primary processes steps, strip, weld, and encapsulate into one functional unit. Mechanical tolerances on the relative positions of the various elements of hardware are established and maintained very closely. The hardware elements are mechanically linked together by a common base of granite. The dimensional precision and inertial stability required for the laser processes are thereby assured.

2.2 System Configuration

The components of the sytems are arranged to provide in-line processing through all steps that end with a finished, tested Flexicon assembly. A perspective view of the Flexicon Automated System is presented in Figure 2.

Design of an Automated Termination Process for Flexible Printed Wiring



A View of
the Automated FLEXICON System

FIGURE 2:

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Flexible Printed Circuits With Integral Molded Connectors

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The automated Flexicon system has, as its central feature, tooling mounted on a computer numerical controlled (C.N.C.) linear slide table which provides x-y motion in the horizontal plane. Programmable control of the position of the tooling relative to the fixed positions of the two lasers and the mold press allow system design to be simplified.

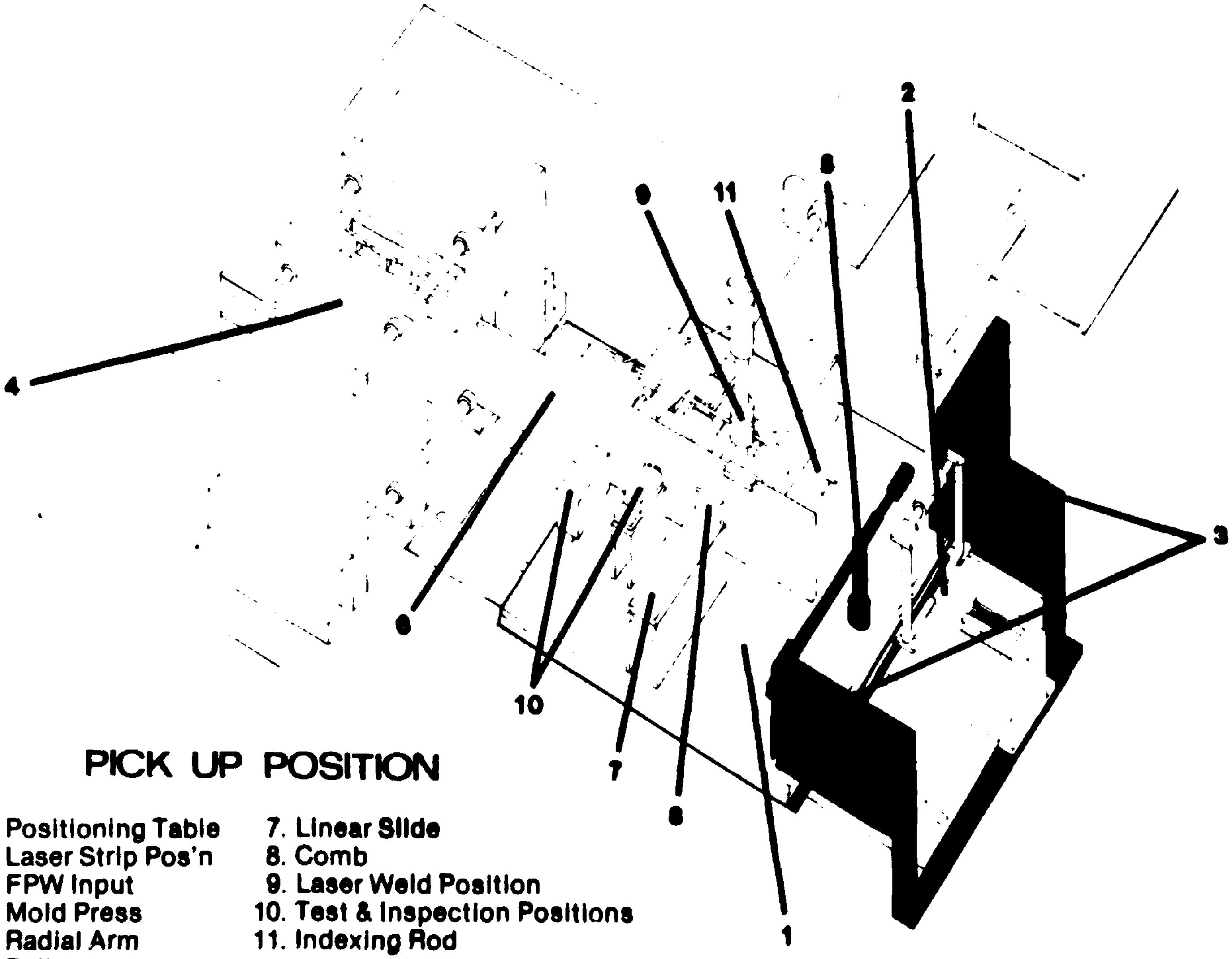
As depicted in Figure 3 the x-y positioning slides are mounted centrally on the granite surface plate. Tooling to support and reference the connector and flex assembly through the welding, test and inspection process is mounted on the positioning tables,(1 in Figure 3).

The facility for CO_2 laser stripping and cleaning (2 in Figure 3) is positioned in the righthand foreground of the surface plate. Note that this laser, as well as the Nd:YAG laser for welding, is referenced to the granite base. Localized laser energy shielding is not shown, for clarity of illustration.

Containers for presenting stacked, pre-oriented FPW to the system (3 in Figure 3) are located on each side of the stripping facility. The molding press is located at the opposite end of the granite base. It is oriented horizontally, (4 in Figure 3).

The radial arm structure, mounted on the positioning table in the foreground (5 in Figure 3), has two functions. The radial arms can be rotated in the horizontal plane. The longer arm is equipped with a vacuum platen which is used to acquire a flex circuit from the pre-oriented stacks and manipulate the flex through the laser stripping and cleaning process. The shorter arm is used to acquire a connector from the connector

Automated FLEXICON Facility



PICK UP POSITION

1. Positioning Table
2. Laser Strip Pos'n
3. FPW Input
4. Mold Press
5. Radial Arm
6. Rail
7. Linear Slide
8. Comb
9. Laser Weld Position
10. Test & Inspection Positions
11. Indexing Rod

FIGURE 3:

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input station and transfer it to the vertical rail. The prominent tooling feature on the positioning table is the rail structure (6 in Figure 3), which supports the assembly in a vertical orientation with the pin rows straddling the top edge of the rail. The rail permits symmetrical access to each side of the connector pin rows and provides vertical clearance for the trailing flex.

On the table are two linear slides, positioned on each side of the rail (7 in Figure 3). Each slide supports a vertical vacuum platen with a comb-like feature at the upper edge, (8 in Figure 3). The comb tines interdigitate with the stripped flex conductors to provide mechanical registration of the flex with the system. The slides can be rotated in the horizontal plane to align the slide's vector alternately between the radial arm for flex transfer to the slide and the weld position at the rail. Welding takes place as the connector and registered flex are transported in the focal plane of the horizontally oriented Nd:YAG laser beam, (9 in Figure 3). Welding is done sequentially, first on one side of the connector and then on the second side. Electrical test and visual inspection stations are also located on the positioning table downstream from the weld station, (10 in Figure 3). This permits concurrent test and inspection of previously welded assemblies.

The overhang of the rail beyond the positioning tables provides space for queueing acceptable assemblies and then moving the table to position the assemblies in between the mold halves.

2.3 System Kinematics

This section will describe in detail the many events that occur in the

automated production of a Flexicon assembly. Referring to Figure 4, a diagram of the overall sequence of events can be seen. First to be noted, is that the system cycle spans the time required to produce three assemblies. Because the encapsulation curing cycle requires a longer time than the other assembly cycle times, it is necessary to queue the welded assemblies until three at one time can be inserted into the matching three cavity mold. Also note, the electrical test and electro-optical inspection take place concurrently with the flex stripping and welding. This is made possible by having the hardware for these functions mounted on the positioning tables.

The first event in the automatic process occurs when the vacuum pick-up platen on the radial arm is brought into contact with the pre-oriented stack of FPW in the foreground. The table backs away from the stack with the circuit held to the radial arm by pressure differential. This event is that illustrated in Figure 3. The radial arm then rotates counter-clockwise 90 degrees in the horizontal plane and commences a series of back and forth passes in the CO_2 laser beam; at the same time it is incremented vertically with each pass. This causes the cover coat to be ablated exposing the copper circuits. This action is illustrated in Figure 5. The stripped circuit is then mechanically cleaned and washed by advancing the circuit into the brushes positioned in line with the laser focal plane.

The radial arm then rotates counter-clockwise an additional 90 degrees. At this point the slide mounted comb is caused to rotate 90 degrees clockwise in the horizontal plane and advance the comb to engage the FPW. This is illustrated in Figure 6. Control of the FPW is transferred to the comb by inhibiting vacuum on the stripping platen and enabling vacuum on the face of the comb. The slide then retracts with the flex attached, rotates 90°

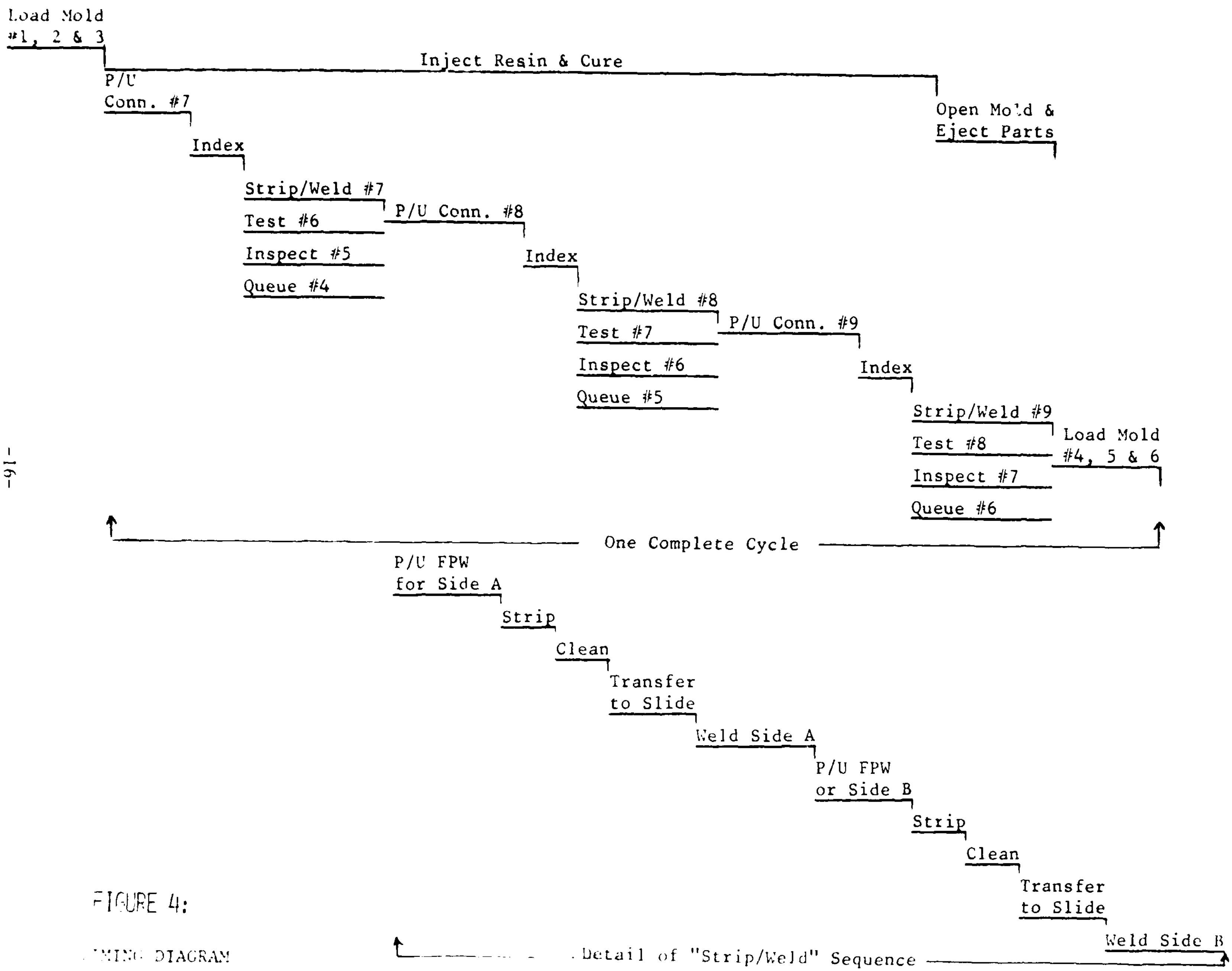
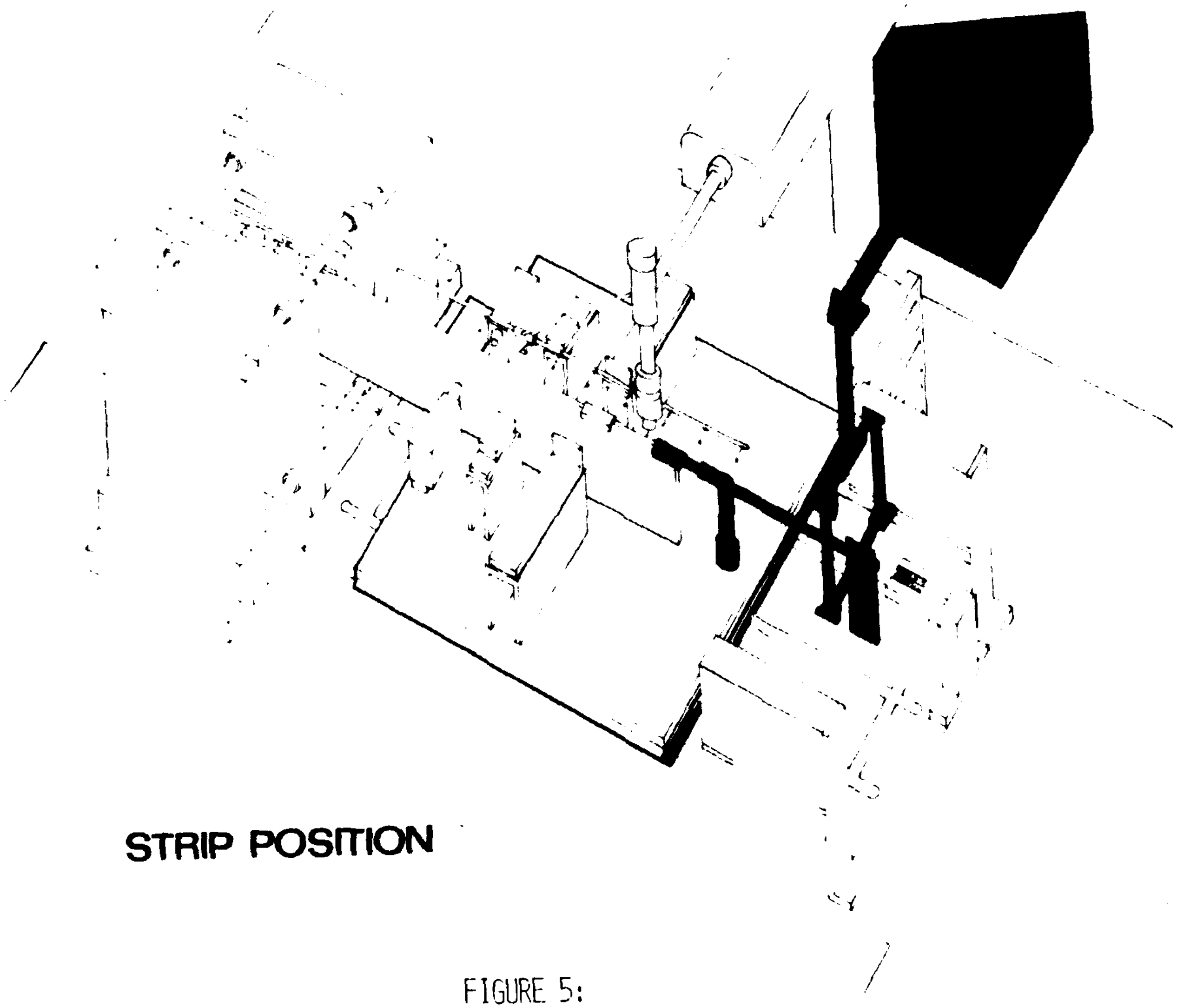


FIGURE 4:

TIMING DIAGRAM

Automated FLEXICON Facility



STRIP POSITION

FIGURE 5:

Flexible Printed Circuits With Integral Molded Connectors

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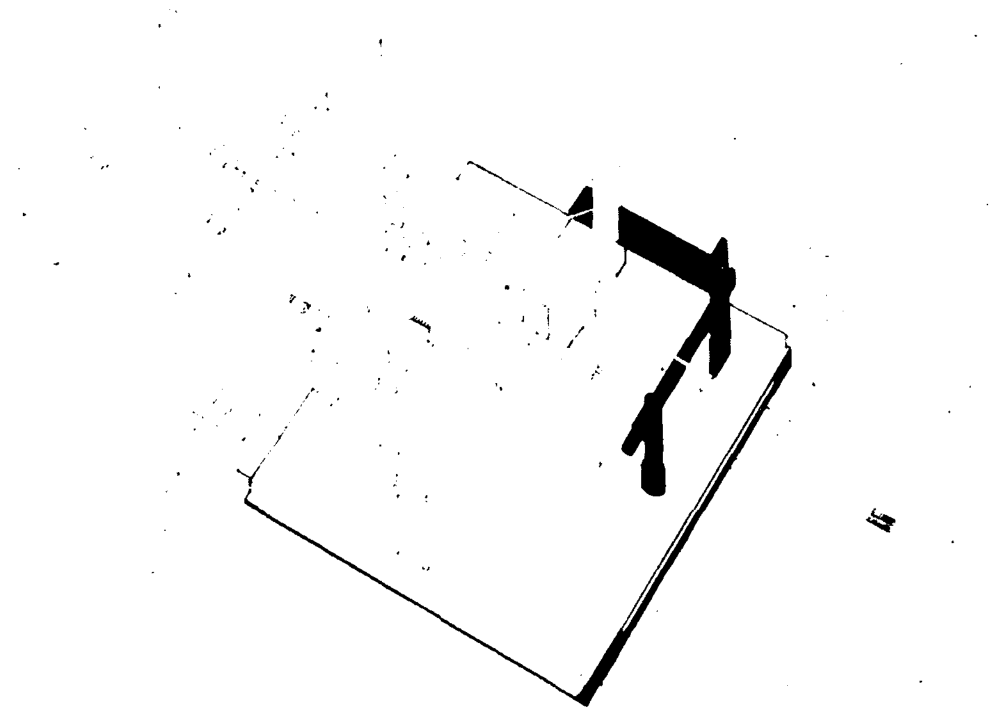

TRANSFER TO COMB

FIGURE 6:

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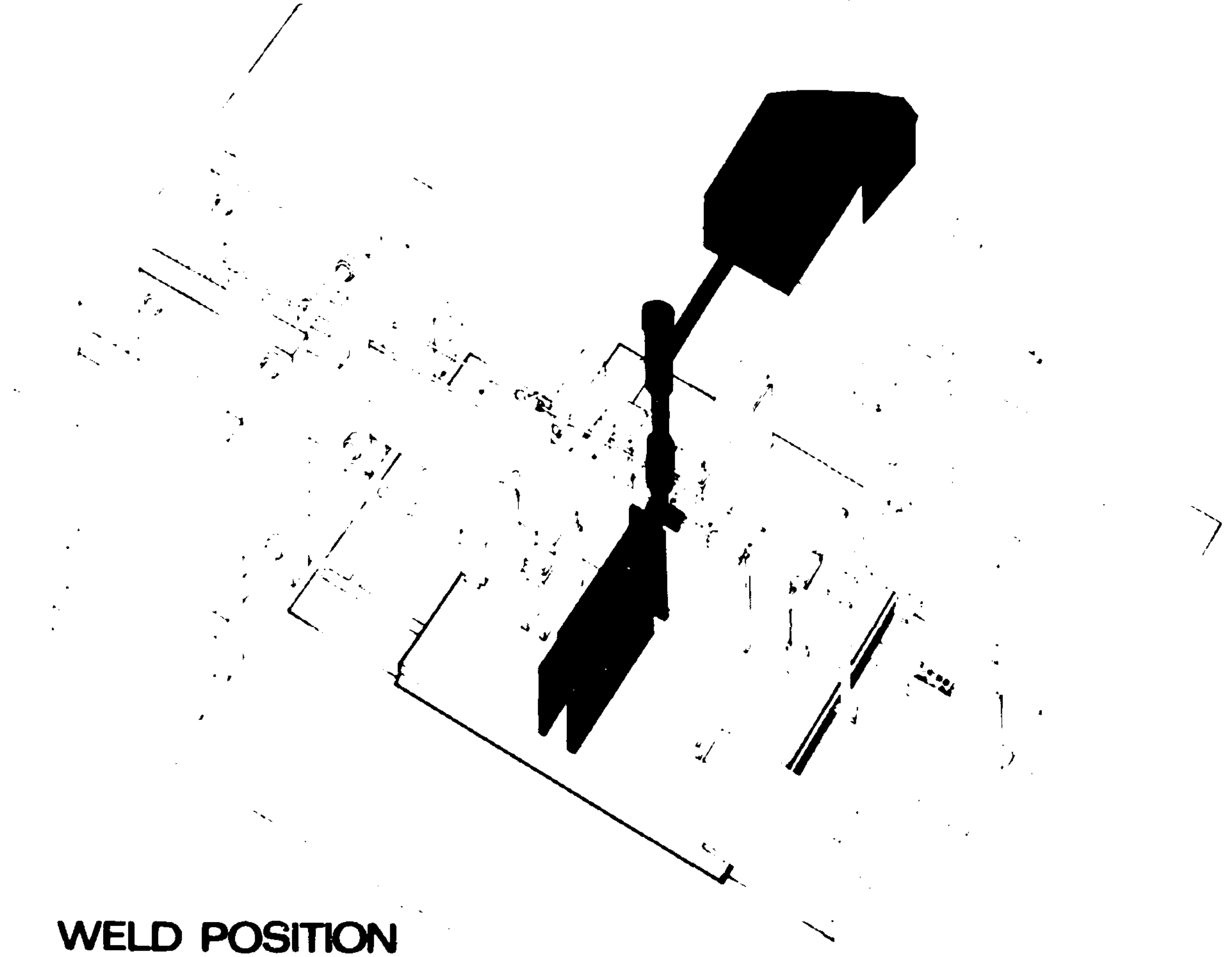
clockwise to return to its start position. Again the slide advances and engages the previously positioned connector, aligning and clamping the circuit leads to the connector pins. This is illustrated in Figure 7. The table then moves the assembly into the focal plane of the Nd:YAG laser and commences the spot welding routine. At the completion of the weld cycle the vacuum is inhibited and the slide retracted to start position. This sequence is repeated again, in mirror image, for the second side of the connector.

During the period when stripping and welding are taking place, previously welded assemblies are being tested and inspected automatically. The slide mounted probes are caused to advance and contact in the weld area to electronically verify continuity and acceptable conductivity of the weld joint. Cameras for the optional optical inspection are positioned next in line on the table.

At this point in the process the table moves to bring the shorter radial arm in line with the connector input station positioned next to the CO_2 laser housing. Through an escapement mechanism, one connector is pushed onto the arm. The arm rotates 90 degrees counter-clockwise to align with the rail.

With the new connector in this position the indexing cycle starts. The entrained connectors are each simultaneously moved to the next station on the supporting rail. This includes moving the connector on the arm to the first position on the rail. Indexing is accomplished by the rod with radial spokes supported by the Nd:YAG laser column, as illustrated in Figure 8. This rod is rotated 180 degrees about its major axis which brings the radial spokes into position between the connectors. The table is then caused to move from left to right, whereupon the connectors, initially moving with the rail, each

Automated FLEXICON Facility



WELD POSITION

FIGURE 7:

Automated FLEXICON Facility

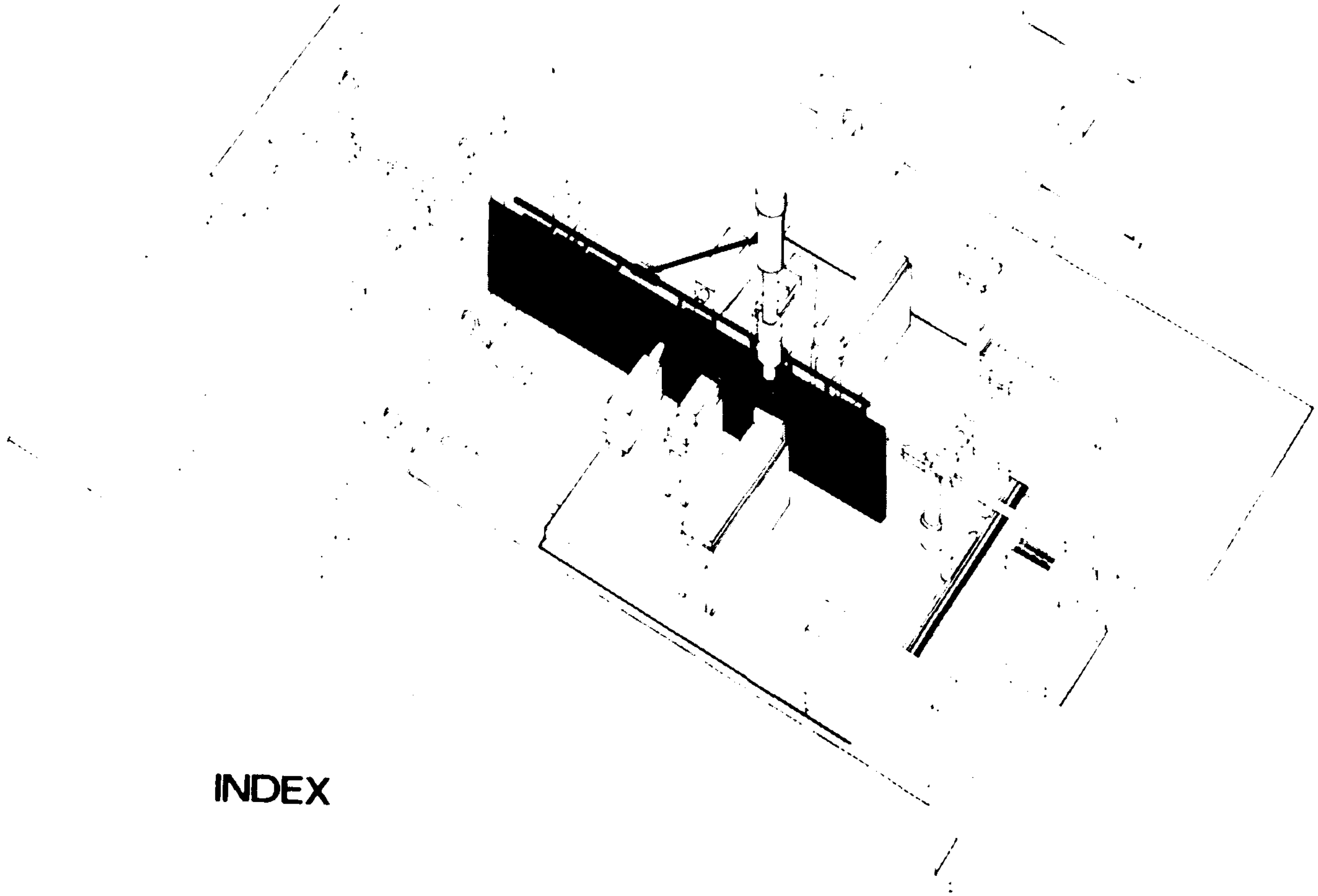


FIGURE 8:

Flexible Printed Circuits With Integral Molded Connectors

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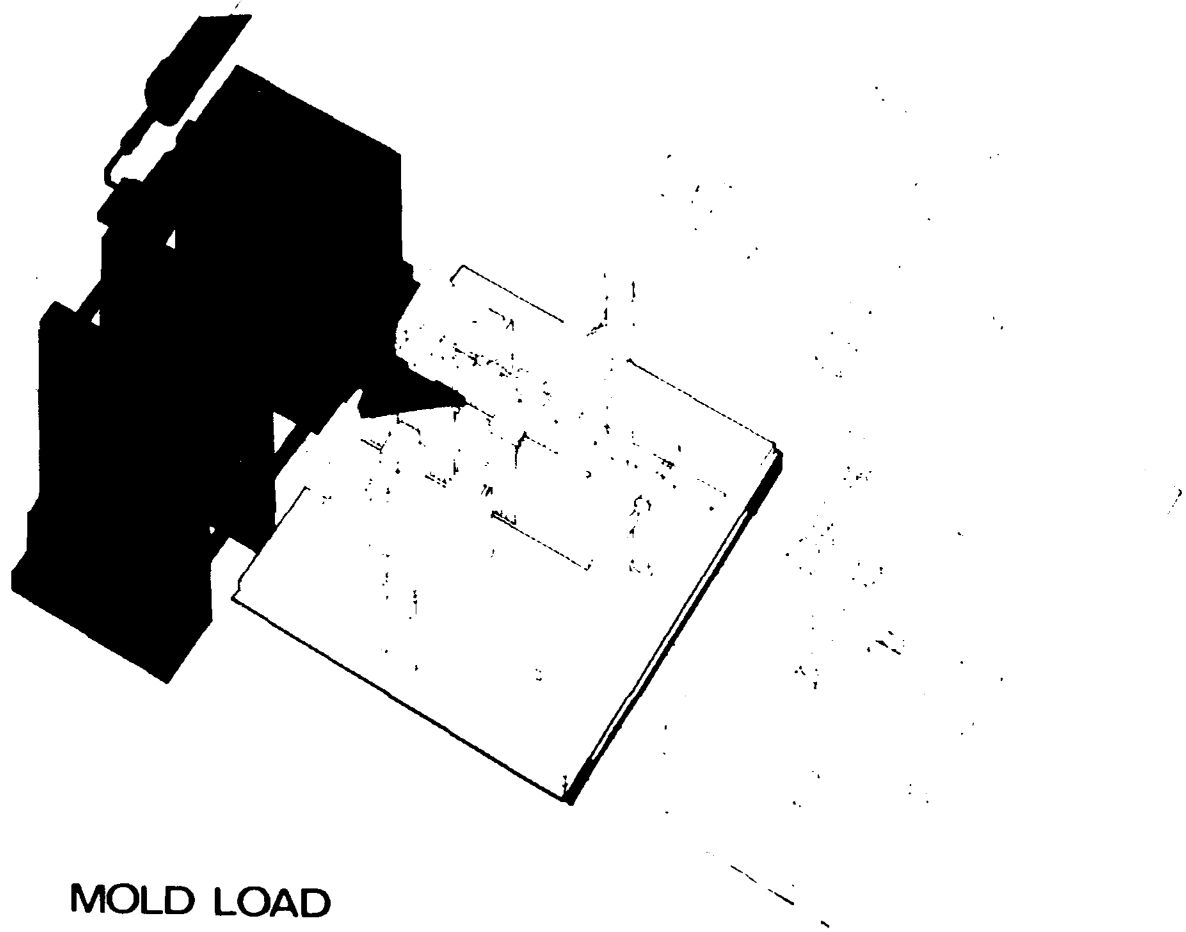
encounter a spoke on the rod. The spoke acts as a stop to the connectors, holding each stationary while the rail continues to move until the next station on the rail is precisely registed with each assembly. The rod is then rotated back to its start position. The next step depends on the status of the assembly queue waiting for transfer to the molding press at the far end of the rail. If the queue is not full, that is, there are not yet three assemblies in the queue, then the sequence beginning with flex stripping will occur again. If, however, the queue is full, then the contents of the queue will be transferred to the mold cavities. In this event the table moves from right to left to bring the assemblies in the mold queue into the space between the mold halves. This event is illustrated in Figure 9. The mold then closes partially, nesting the connector bodies in the mold cavities. The rail is then withdrawn, leaving the assemblies in the mold. The mold then closes completely and the molding cycle commences. The molding cycle ends when the mold is opened and Flexicon assemblies are ejected from the cavities. The assemblies fall between the mold halves to a tray located below.

2.4 System Control

As stated in the section on Design Strategy, the Flexicon System is designed for programmable automation in which hardware tooling is minimized and the advantages of control by software are fully exploited. A microprocessor based C.N.C. system is used for the following functions:

- Positioning commands for the two axis positioning table
- Firing commands for each laser, coordinated with the position of FPW or assembly
- Control of all other system events through external porting of program commands to interfacing hardware, such as solenoid valves.

Automated FLEXICON Facility



MOLD LOAD

FIGURE 9:

Flexible Printed Circuits With Integral Molded Connectors

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All sytem events which are of a routine nature (not subject to change when a style change occurs) are controlled by programmed sub-routines. They are cued through external ports of the microprocessor control. Some of the sub-routines which are sequential in character are:

- Indexing
- Connector pick up and transfer to rail
- FPW pick-up and radial arm motion
- FPW transfer from radial arm to slide
- FPW Cleaning Cycle
- Mold Closure Cycle
- Load Mold Cycle
- Injection Cycle
- Laser Cover Gas control
- Nd:YAG Laser Beam Steering
- Continuity Test sequence
- Inspection Sequence (Optional)

3.0 DESIGN REQUIREMENTS

3.1 System Foundation

To support and inter-relate process hardware, a platform which has sufficient strength and dimensional stability to support the hardware and maintain alignment of laser optics with the positioning table tooling is required. The platform must also have sufficient mass to dampen reaction to positioning table movement. A granite surface plate meets these requirements and is recommended as the system foundation.

3.2 The Lasers and Beam Steering Optics

The Stripping Laser

The requirement to selectively ablate the FPW insulation cover while leaving the copper circuit undisturbed dictated the use of a CO_2 laser. Equipment with an average power output range of 150 watts is required. A pulse repetition rate of 500 Hz controllable by external command is also required.

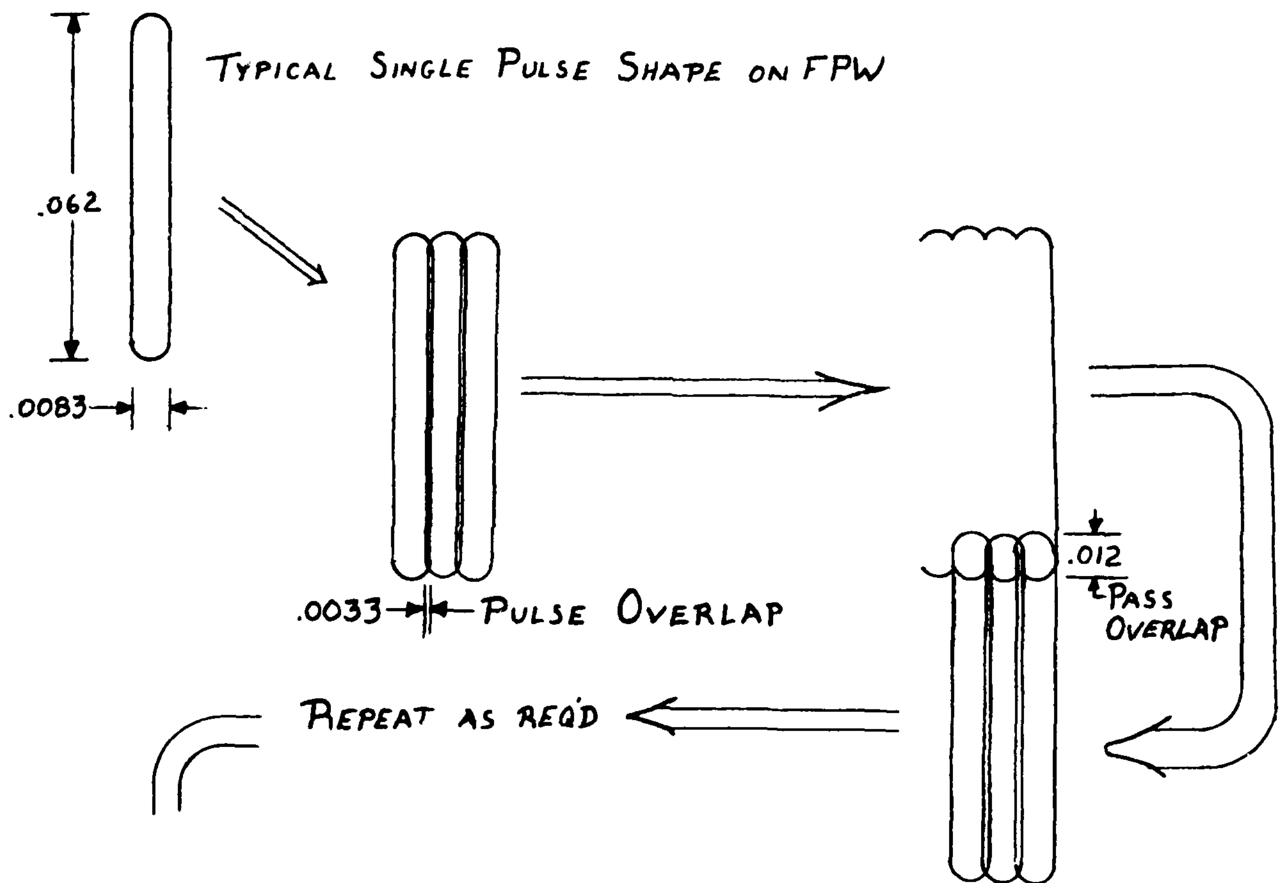
The beam delivery optics splits the columated beam 50/50 and directs it to both sides of the FPW by a series of mirrors and lenses. The .0314 inch diameter coherent beam is c rged to .062 inch in a 5:1 beam expander/condenser. The beam is then directed to each side of the FPW by a series of 45 degrees beam benders, and focused on the FPW through an anamorph lens which focuses one axis of the cross section of the beam to a width of .0083 inches. The resultant cross-section of the focused spot is therefore

.062 inches x .0083 inches. The split beam power of 75 watts each, focused to this spot size of .00051 square inches gives the required power density of 1.46×10^5 watts/in^2. The opposed optics are not mounted co-axially, but are offset in the horizontal plane sufficiently to prevent interaction between the two laser beams.

The stripping process is performed by making successive passes with the flexible printed circuitry between the focused beams. The motion of the material must allow for sufficient overlap of the spot patterns to ensure complete removal of insulation. FPW transported in a path parallel to the .0083 inch width of the beam spot should receive a beam pulse every .005 inches. For each succeeding pass the piece should be indexed .050 inches in the direction parallel to the length of the spot size. Each pass should be pulsed and indexed the same amount until the desired width of insulation has been removed. Figure 10 shows the movement of the FPW through the beam. At a table speed of 2.5 inches/sec, a pulse rate of 500Hz is required to achieve a pulse every .005 inches. This would allow a pass to be made every second on a two-inch wide piece of FPW. A strip width of .250 inches at this rate would be completed in five seconds.

The Welding Laser

The requirements for welding copper and gold plated leads and connector pins narrowed the choice of lasers to a Neodymium:YAG type of laser. The high reflectivity of copper to the wavelength of the CO_2 laser makes it highly impractical as a welding tool for this particular application.



Each pass of laser across FPW consists of multiple overlapping pulses

After each pass, the FPW is incremented vertically to create a series of overlapping passes until the desired strip height is achieved.

Figure 10: Stripping Beam Overlap

The power requirements can be readily handled by a 200 watt average power laser. This is a conservative estimate which allows higher production rates as the manufacturing technology progresses.

At the present stage of development, which is adequate to meet our automated production requirements, the welding is accomplished at a speed of approximately 24"/min at a repetition rate of 16 pulses per second or higher. The present technique requires the accurate firing of the laser so that each lead receives two pulses approximately 4 joules each depending on the thickness of the conductors.

A lens with a 4" focal length was used with these parameters, and defocusing about 10 mils away from the part appeared to produce better results.

A closed circuit TV monitor simplifies focusing, but light conditions often affect accuracy of focusing and therefore should be assisted by a dial indicator with .001" graduations. The pulse width capabilities should be from 3 to 7 milliseconds, with higher pulse widths for heavier conductors. The TV monitoring can also help avoid operator fatigue in high volume production facilities.

To ensure accurate energy density, uniformity of pulse shape and energy is required. This can best be accomplished by the use of an oscilloscope to monitor the operation and to facilitate adjustments. The scope can be a permanent part of the set-up whereby the operator can adjust the energy output to give a value to match the wave height and shape prescribed for a given task. This procedure will compensate for lamp degradation and can be used to detect abnormal operation of the equipment.

In development of prototype tooling, it was determined that the tolerance on spacing between parallel rows of connector pins was too great to allow effective clamping of the flexible circuitry to the connector pins on both sides of the connector at the same time. Therefore, one side is clamped, welded, and unclamped before the second side is clamped. A means of directing the focused laser beam in the horizontal plane and rotating it 180° to scan each side of the connector is required. Figure 11 illustrates the beam steering configuration. A focusing lens with 4" focal length is inserted in the expanded and columnated laser beam. Three inches away from the lens, a front surface gold-plated mirror is supported in the focused beam. The mirror is supported on a shaft which allows the mirror to be rotated 90 degrees in the horizontal plane between fixed stops. Rotation of the mirror through a 90 degree arc has the effect of redirecting the focused beam 180 degrees. Since the mirror reflects greater than 98% of the incident laser energy, it is important that the mirror surface be maintained absolutely clean in order to preserve this capability. This is achieved by housing the lens and mirror in a closed structure with apertures located in the side wall of the structure for beam porting. Positive pressure is maintained with dry inert gas to prevent dust or weld spatter from degrading the mirror surface.

3.3 Control Hardware and Positioning Tables

Control Hardware Functional Requirements

- Microprocessor-based computer numerical control

- Simultaneous two axis control of positioning table - linear and circular interpolation

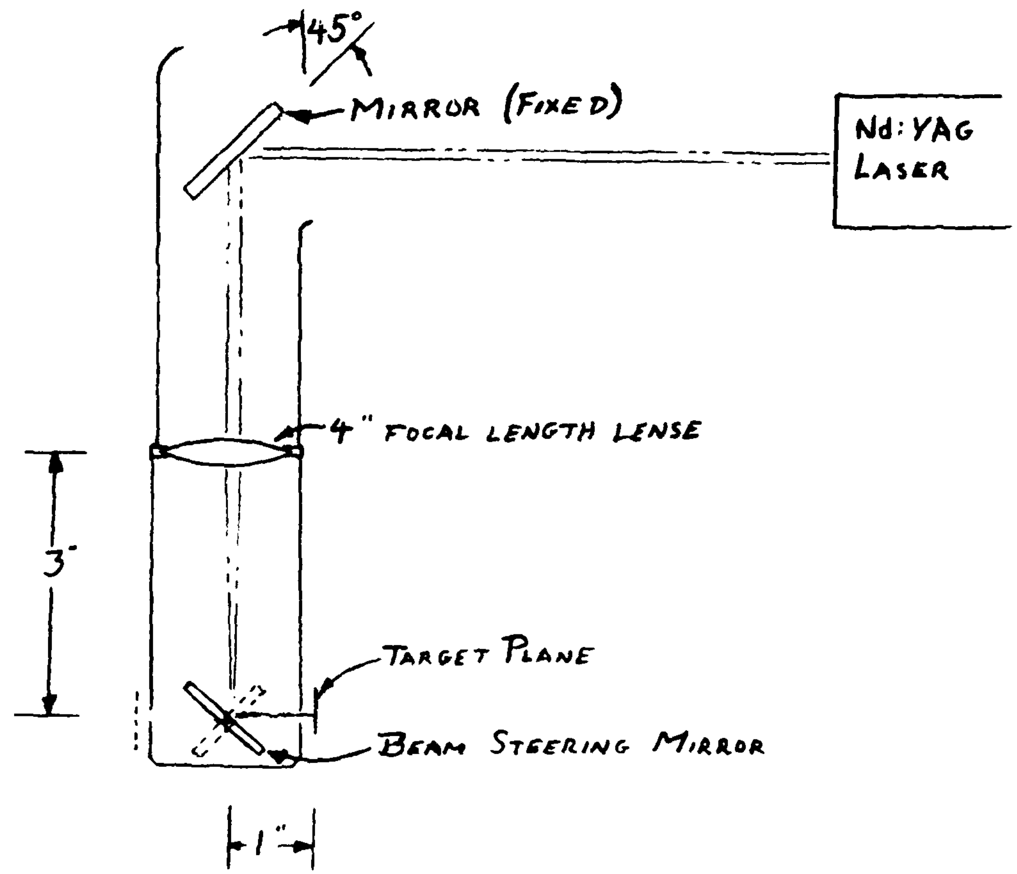


FIGURE 11: Nd:YAG BEAM DELIVERY OPTICS

- Programmable Input/Output Ports
- Programmable Laser Fire Logic
- Suitable memory for the required programs
- Programmable, feed, dwell, absolute/incremental position
- Reference and zero set
- Optional stop
- Feed override - 0-100%
- Manual Data Input and edit capability
- Callable subroutines

Positioning Table Functional Requirements

The tables are to be machine tool type, motorized, ball-nut and lead screw linear slide positioning tables. One axis, aligned with the rail should have a positioning range of 18 inches. The second compounded axis working at right angles to the rail should have a positioning range of 6 inches.

3.4 Connector Rail

Functional Requirements

The connector rail is both figuratively and literally the backbone of the tool. It supports the Flexicon assembly in the vertical plane and provides unobstructed clearance for the flex circuit. Its thickness is scaled to receive the connector, with pin rows straddling the rail. This allows the connector to be moved to process positions along the rail by sliding motion.

The connector rail must meet the following design requirements:

- The rail must have a vertical dimension sufficient to provide clearance for the FPW styles anticipated.
- Rail thickness should be .003 - .005" less than minimum spacing between pin rows.
- The rail should provide for localized insert features which are complimentary to the welding and test stations; that is, clearance for the alignment comb and dielectric backing at the test station.
- The rail should provide a simple change-over method to accommodate changes in connector styles.

3.5 Radial Arm, Flex and Connector Input

The radial arm provides the means for inputting pre-oriented and stacked FPW and connectors into the automated system and for manipulating FPW through

stripping and cleaning. Its operation is described in Section 2.3, System Kinematics. It is positioned on the tooling table and in line with the input end of the rail. This strategic location provides access for the radial arm to the flex input, the connector input, the stripping laser and cleaning station, the transfer slides and the rail.

The radial arm has these features:

- A verticle column which provides bearing support for the two radial arm extensions. The radial arms can be rotated about the axis of the column.

- The longer arm, which is used to hold the FPW, has a two sided vacuum platen positioned at its extremity. The platen faces are pneumatically isolated from each other so that the vacuum source can be switched from one face to the other. The platen is used to acquire and hold FPW, from input through stripping, cleaning and finally, transfer to the comb.

- The arm should be cammed, in fixed increments, in the verticle axis to accommodate the multiple-pass laser stripping process.

- The shorter arm is used to acquire a connector from the connector storage tray and transfer it to the first position on the rail. It is assumed that connectors will be presented to the system in an orderly manner, that is, oriented and aligned with pin tails straight and parallel with no kinks or bends which would interfere with subsequent processing. To meet this requirement, the handling and input of connectors in rigid plastic tubes is strongly recommended.

- The arm has a cross-section at its extremity which is the same as the rail. When the arm is rotated into alignment with the input station a connector is pushed onto the arm. When the arm, with connector in place, is rotated into alignment with the rail the indexing sequence causes the connector to be transferred to the rail.

3.6 Flex Stripping and Cleaning

The arrangement of two opposed laser beams having a common focal point is described in Section 3.2, Lasers. With the FPW held in place on the radial arm's vacuum platen, the FPW is aligned in the laser beam focal plane. Programmed motion of the tooling table moves the FPW into the laser beam. The first pass causes a strip of cover material .062 inches wide to be ablated from both sides of the flex. To produce a wider stripped zone the radial arm is indexed upward .050 inch, presenting a new parallel strip of material to the laser beam on the return pass. The nominal .250 inch stripped zone required to register with the alignment comb used in the subsequent welding process would therefore require that five passes be programmed with a .050 inch verticle displacement between each pass.

In the development work, a narrow margin of insulating material was intentionally left at the leading edge of the FPW. This selvage edge serves as a useful binder to retain the alignment of the exposed copper track through mechanical cleaning.

The cleaning process is necessary to remove particulate residue which might affect the absorptivity of the copper surface when presented to the

subsequent laser welding process. A pair of soft, nylon bristle brushes are used to wipe away residue. The FPW is passed between the opposed pair of brushes immediately following the final stripping pass. A solvent wash completes the cleaning process.

3.7 Flex Transfer Slide and Comb

The arrangement of the slides, FPW, connector, and the rail member is detailed in Figure 12. The transfer slides provide the link between the radial arm and the weld station.

Functional Requirements:

- Transfer stripped and cleaned FPW from the radial arm to the weld station.
- Register flex leads with connector contact tails.
- Hold the FPW leads and contact tails in intimate contact in the weld target area but not obscure the target from the laser beam.

The first requirement is met by using a pair of linear ball slides positioned on each side of the rail. Each slide is fitted with a precision, comb-like fixture, mounted vertically at the end of each slide. The base of each slide is fixed to the supporting pedestal by a precision bearing. This allows the slide vector to be rotated in a 90° arc between the FPW transfer point and the weld station. Actuation for the slide rotation and for linear extension can be accomplished with pneumatic cylinders. The comb features are

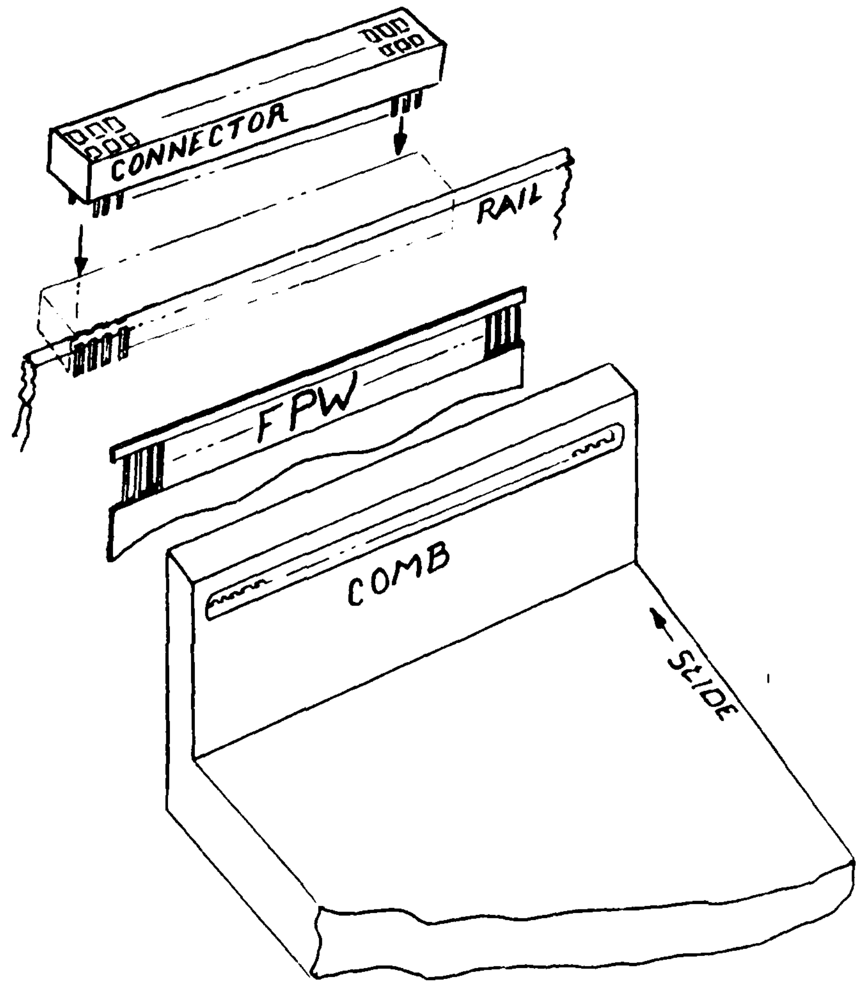


FIGURE 12: EXPANDED VIEW SHOWING RELATIONSHIP OF COMB, FPW, CONNECTOR, AND RAIL

illustrated in Figure 13. The raised fingers of the comb interdigitate with the stripped FPW leads, providing the required registration of the FPW. The FPW is held to the face of the comb by the vacuum porting in its front surface. The required intimate contact between the FPW lead and connector contact tail is accomplished when the comb, with FPW in position, is brought together and registered with the connector which has previously been positioned on the rail. Pressure points above and below the weld target area are established by the comb pressing against the rail. Note that the comb fingers also interdigitate with connector contact tails to assure adequate alignment of FPW leads with the connector.

3.8 Welding

In the design of welding tooling for flexible circuitry to connectors, the following considerations are important.

Surface Condition

- The surface must be uniform with respect to absortivity of laser energy at the Nd:YAG wave length. In this particular case, the welding of copper conductors, where the insulation has been removed, a slightly oxidized surface not only absorbs energy more readily but also requires less energy to accomplish the same amount of melting.

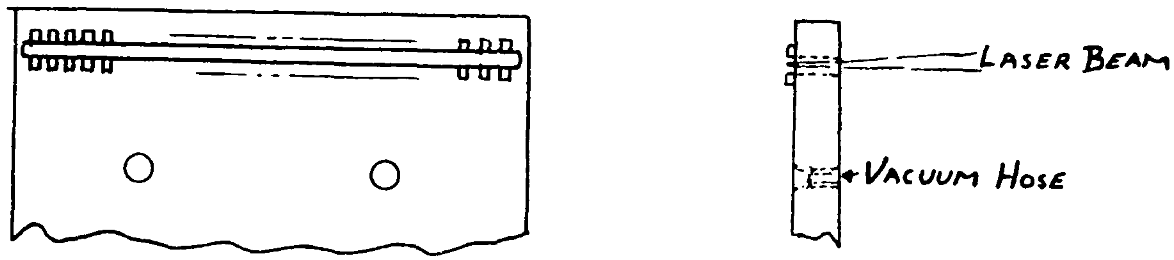


FIGURE 13: COMB FEATURES

- Depending on the FPW fabrication process, some oxides are retained after the ablation process. Other methods of cable preparations may require oxidation of the shiny copper surface. Oxidation of one aide of the flex circuit only or oxidizing both sides and removal of the oxide on the mating side complicates the procedure, but it is a viable one if control samples are welded for each batch of flex that is oxidized. Further work has shown that a more reliable and simpler technique is to strip the flex from one side only. The flex circuit now has the insulation removed between the conductors and from one side of the conductors. The thin selvage keeps the conductors in line for fixturing. The cleaned side is interfaced with the connector pins. The laser beam now strikes the side with the insulation. The insulation helps distribute the energy of the 1.06 micron wavelength laser, and there is sufficient energy to cause melting and fusion of the conductor and connector pin. The remaining small amount of char residue is easily removed by brushing or fine abrasive air blasting. The reliability of this process and additional latitude of the parameters makes this the most promising method for joining the flex circuits to the connector pins.

- The surface must be free of any contamination, specifically organic materials. This type of contamination vaporizes during welding causing changes to the opaqueness of the plume and thereby influencing the energy density and results in unsatisfactory welds.

- Dull nickel plating should be substituted for gold.

Fixturing and Joint Designs

Spacing

- The simple lap joint consists of placing the flat conductors of the flex circuit directly over the connector pins. Cummulative errors in the flex circuit spacing can cause a serious misalignment problem that will result in incomplete or unsatisfactory welds. Automated systems will have difficulty with fixturing flex circuits and connectors if spacing is not uniform and identical, and the weld appearance will also vary and may make inspection somewhat difficult.

Contact

- Metal to metal contact is important and the parts should be held in intimate contact for a length of 1/16 to 3/32". Selvage thickness should be the minimum width possible and the width of the stripped area should be wide enough to permit uniform pressure at the contact points.

- Parts should not be in tension or have the tendency to move while being welded. This should be controlled by the fixturing. Self-aligning precision fixturing that applies uniform pressure over the span of the contacts is a very important requirement. If parts are not in intimate contact, the copper conductors will melt back and not join to the contact tails.

- Gas shielding is maintained principally to keep the optics clean and stabilize the ablation/welding operation.

Weld Parameters

- Welding is done "on the fly" using a CNC programmable controller that controls the motion of the part as well as the pulse rate firing of the laser. The laser shutter is closed initially when the firing starts to allow stabilization of the pulsing output. Pulse rates are such that each conductor receives a minimum of two pulses. For the 20z copper conductors in combination with the Hughes and Amp connectors, the following set of parameters produced satisfactory welds when the beam was welded through the insulation.

Type	Pulse Rate/Sec.	Avg. Power Watts	Speed In Min.
Male Amp	16-18	8-11	10
Female Amp	60	22	20
Male Hughes	16-20	13-15	10
Female Hughes	16-20	13-15	10
Armel 131			
Male Program	16	42	10

Control samples should be welded at the start and during each lot of material to insure reproducible absorbivity and verify parameters.

Specific hardware design requirements incorporating the above process requirements are specified in Section 3.7, Flex Transfer Slide and Comb.

3.9 Weld Test and Inspection

After welding, the inspection of the welds for sufficiency can be

performed on 100% of the joint by four basic techniques. These are resistance check, visual pattern recognition, acoustical emission, and laser thermal inspection.

Laser Thermal Inspection is the observing of the thermal signature of weld joint after being hit with a laser beam. This could be integrated into the welding operation by having a sensor read the thermal information immediately after the laser welding operation.

Acoustical Emission involves the bombardment of the welded joint ultra-sonically and observation of the response. This is a presently available technique. It would involve a separate station between the welding and molding operations.

The simplest method would involve a resistance check of the weld. A conductive back plane with a bar across the connector tails to ensure contact would be used. A row of pointed contacts would engage the FPW circuits. The contacts would be spring loaded to ensure a low resistance path to the circuits. The contacts could be centered on a grid pattern that ensures contact with any configuration of flex circuits. Computer control would be used to scan across those contacts for each configuration to take the resistance reading and compare against the known resistance. This technique is similar to that used by DITMCO to test printed circuit boards.

Optical inspection, or pattern recognition, would involve the optical scanning of the finished joints. Welded samples have been tested to the extent that two very clearly identifiable extremes can be shown to exist on each side of a good weld. If insufficient energy is applied, the copper

circuit forms a ball effect. If the energy supplied is too much, then a burn-out of material occurs. Both of these features are very compatible with processor pattern recognition techniques, and could be set up as the extremes of an accept, reject criteria.

Of these four basic approaches, the continuity test approach is the simplest, least expensive to implement. If a non-contact approach is desired, then the pattern recognition could also be implemented.

3.10 Assembly Indexing

In order to progress the assembly through successive steps, a method of periodically fixing their positions in space while the rail is translated beneath them to the next station is required. A rod, oriented horizontally above the rail and supported in the Nd:YAG laser column, provides the fixed reference stops. These stops are radially mounted pins positioned along the rod at each connector spacing interval.

When indexing is to occur the rod is first rotated to orient the pins in the space between the connectors. The position of these pins relative to each other determines the pitch interval which results, and should be held to a plus or minus .001 inch tolerance, non-accumulative, along the rod axis. Maintenance of precise pitch interval assures the required registration with station features in the rail.

3.11 Encapsulation and Assembly Outfeed

The purpose of molding of the welded flexible printed wiring/connector

assembly is to provide mechanical strength of all the components and to provide protection against environmental contaminants. The system selected for encapsulation is reaction injection molding using a hydantoin epoxy resin system. The system is lightly loaded with a mica filler to help seal the mold against leakage and to improve release of the molded connector from the mold. The hydantoin epoxy provides excellent adhesion to all the components at the same time providing electrical insulation and protection against moisture. The prepared compound is injected into a mold which is preheated to 150°C and is held there under light pressure for about 5 minutes or until strong enough to demold after cooling using ejection pins.

The main features of the molding equipment design are:

- flatness and sealing of the mold
- injection port design
- gating and venting of the multiple molds
- heating and cooling of the mold
- mold release and ejection mechanism
- clamping press for the mold

3.11.1 Flatness and Sealing of the Mold

The usual material is water hardened tool steel with subsequent

hardening. Surface flatness should be 0.0002 on all mating surfaces and all pinned surfaces should be counterbored to eliminate expansion. Sealing of the connector body and the FPW where it enters the mold is accomplished by means of a silicone rubber gasket of shore A50 Durometer inserted in grooves of sufficient depth (approximately .19 deep) to create an expansion of approximately .03 on a temperature differential of 120°C.

3.11.2 Injection Port Design

A seal for the injection of low viscosity liquids into the mold is provided by having a wedge-shaped or conical shaped Teflon plug pressed tightly against the injection port. This can also be accomplished with a silicone rubber gasket either foamed or solid rubber placed in a counterbored hole around the injection port. A liquid tight seal can be made with only 5 PSi air pressure on the injection port ram.

3.11.3 Gating and Venting

It has been determined that a gate opening of .016 is optimum for liquid flow in the heated mold and a vent opening of .002 will allow expulsion of air without loss of contents.

3.11.4 Heating and Cooling

A ground surface is required on all surfaces coming into contact with the platens of the mold clamping press.

The mold should be electrically heated and water cooled so that the desired cure is completed within 5 minutes.

3.11.5 Mold Releasing and Ejection Mechanism

The preferred mold release for the hydantoin epoxy is a proprietary coating called NEDOX applied on steel surfaces by General Magnoplate Corporation, Linden, New Jersey. This surface consists of an electro-deposited chrome-nickel alloy which is extremely porous and which readily accepts an infusion of polytetrafluoroethylene (PTFE) which then acts as a mold release.

The multi-cavity mold requires an ejector rod system in order to eject the molded connector. In addition the molded connector must be ejected from a cool mold in order to avoid damage to the part during ejection.

3.11.6 Clamping Press for the Mold

The clamping press for the mold should be hydraulically operated, hold the mold closed under a pressure of 1450 pounds per square inch, and be capable of accepting mold inserts on a standard mold base size. Timing of all of the operations required, such as automatic loading, closing, holding, and opening, will be controlled by the microprocessor.

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